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Effect of different drip fertigation methods on maize yield, nutrient and water productivity in two-soils in Northeast China

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ABSTRACT

Maize growth in Northeast China is suffering from climate change (seasonal drought, cold springs) and low nutrient use efficiency caused by one-time fertilization. Drip fertigation is widely used in vegetable and fruit plant production, yet an efficient, practicable and cost-effective drip fertigation system is lacking for maize production. A two-year field experiment was conducted to evaluate the potential of different drip fertigation methods for increasing maize yield, and water and nutrient use efficiency in sandy and clay soil. Five irrigation methods were applied in each soil: conventional (rain-fed, CK), drip irrigation (DI), surface drip fertigation (SDF), fertigation plus plastic film mulching (SDFP), and subsurface fertigation (SSDF). Compared with rain-fed method (CK), water optimization by DI increased grain yield by (28% in sandy soil and 12% in clay soil), partial fertilizer productivity (PFP) and nitrogen (N), phosphorus (P) and potassium (K) uptake, without effect on water productivity (WP) in both soils. The optimization of both water and nutrient management by SDF increased grain yield by (41% in sandy soil and 17% in clay soil), PFP and NPK uptake, at greater extent than DI. Furthermore, SDF also increased the water productivity in both soils. Compared with DI, SDF increased post-silking N in both soil, and K accumulation in sandy soil. There was no significant difference in yield and PFP between SDF, SSDF and SDFP methods in both soils. In sandy soil, the net profit of DI, SDF, SSDF and SDFP was 13%, 28%, 31% and 10% higher than that of CK, respectively. In clay soil, However, No obvious advantage in net income was found in either DI or fertigation treatments. SDF and SSDF are recommended to increase maize yield, water and nutrient use efficiency, as well as economic benefit synchronously in sandy soil.

1. Introduction

Food security is a growing concern worldwide (Barrett, 2010). Continuing population and consumption growth will mean that the global demand for food will increase for at least another 40 years (Godfray et al., 2010). However, agriculture faces great challenges of global climate change, resource depletion, and environmental degradation (Chen et al., 2014b). Drought has been one of the world's most widespread climate disasters affecting agricultural production (Pelling et al., 2004). It is reported that area percentages of high and very high agricultural drought hazard zones are approximately 23.57 and 27.19% of the total agricultural area in the world (Geng et al., 2016). In China, water resources are also in serious shortage (Li et al., 2009).Improving water use efficiency is important to safeguard food security (Sun et al., 2016). Because of the enormous contribution to increased crop production, fertilizer is used in every region of the world and the application has been enhanced by farmers all over the world (Motesharezadeh et al., 2017). However, fertilizer use efficiency is low all over the world. In China, for example, the mean use efficiency of N, P, K fertilizer is only 27.2%,11.1% and 31.1%, respectively (Zhang et al., 2008).Therefore, there is a need for efficient use of water and fertilizer resources to ensure sustainable food production.

Drip irrigation is one of the most efficient methods of watering crops. This technique offers improved yields, requires less water, decreases the cost of tillage, and reduces the amount of fertilizers applied to the crop (Lekakis et al., 2011). Drip irrigation is widely accepted for crop production in areas of water scarcity (Fanish et al., 2011). Numerous reports have summarized the potential advantages of drip irrigation compared to other irrigation methods, such as furrow, alternate furrow and check basin irrigation methods. For example, drip irrigation increases water use efficiency, crop yields and quality, and improves fertilizer and other chemical application (Hernandez et al.,

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1991; Phene et al., 1991; Camp, 1998; Pablo et al., 2007; Sampathkumar and Pandian, 2011). Drip irrigation is often used in the production of high value produce such as fruits, nuts and vegetables (Hebbar et al., 2004; Rajput and Patel, 2006; Devasirvatham, 2009). However, there is growing interest in applying drip irrigation to lower value field crops, such as cotton and maize (Hodgson et al., 1990; Ünlü et al., 2011; Wan et al., 2012). In the United States, some farmers use subsurface drip irrigation because the fertigation system can be used for several years (Lamm and Trooien, 2003; Enciso-Medina et al., 2011). However, previous studies indicate that the effect of this technique for maize crops is not stable. Lamm (2016) summarized the findings of more than a dozen studies which demonstrated that under subsurface drip irrigation, crop yields range widely – from −51% to +30% – with an average positive increase of 4% across all studies.

Drip fertigation is a modern innovative irrigation method, by which fertilizers are applied along with irrigation water through a drip system to increase fertilizer use efficiency and boost crop yields (Bar-Yosef, 1999; Solaimalai et al., 2005; Fanish et al., 2011). A properly designed drip fertigation system can maximize crop water and nutrient uptake, while minimizing nutrient leaching (Gardenas et al., 2005). Drip fertigation can be applied to the soil surface and subsurface. In some cold areas in China, drip fertigation is used together with plastic mulching (Ma et al., 2004, 2007; Wei and Chen, 2011). Different drip fertilization methods can have varying effects on nutrient and water distribution in the soil and plant root growth, and therefore plant nutrient uptake. For example, it was found that compared to surface drip fertigation, subsurface drip fertigation moved the center of the root density to a deeper depth and increased ear yield (Hernandez et al., 1991; Phene et al., 1991). However, the advantage of subsurface drip fertigation is found to closely relate to soil type. In highly permeable coarse textured soils, water and nutrients move quickly downwards from the emitter, making it difficult to wet the near surface zone if emitters are buried too deep (Cote et al., 2003). Recently, many research efforts have been aimed at improvement of corn yield (Liu et al., 2014), irrigation water efficiency (Liu et al., 2011), assessment optimal N level, N management and yield-increasing potential under drip irrigation in the Northeast of China (Sui et al., 2018; Wang et al., 2017). However, very little research has been done on the different drip irrigation methods to assess corn yield, nutrient and water productivity and nutritional properties under different soil types.

The Northeast China Plain is China's major maize production area, accounting for 30–35% of the country's production (Yang et al., 2007; Zhao and Yang, 2009; Chen et al., 2014a). Maize in this area is rain-fed. Precipitation varies widely between seasons and years, and water deficit frequently occurs during the maize growth season (Dong et al., 2011; Lu et al., 2014), especially in the west part of Northeast China where the soil is mostly sandy and the weather is cold in the spring (Ma et al., 2004; Zhao and Yang, 2009; Yang et al., 2015). Fertilizer use efficiency is low in this area because fertilizers are overused and typically all the fertilizers are applied at planting (Gao et al., 2010). To face these challenges, the Chinese government has encouraged the farmers to adopt various drip irrigation and fertigation methods to increase maize yield while reducing water and fertilizer input. Nevertheless, less research has been done to compare the effect of the different fertigation methods on maize yield, and water and nutrient use efficiency under different soil types and weather conditions. Also it is not clear which of the methods is cost-effective and more practicable. These information is valuable not only for the farmers to optimize their fertigation system, but also for the government to make reasonable subsidy polices supporting the farmers to setup fertigation systems. In the present study, a two-year field experiment was conducted to evaluate the effects of different drip fertigation methods on maize yield and water and nutrient use efficiency in sandy and clay soils in Northeast China.

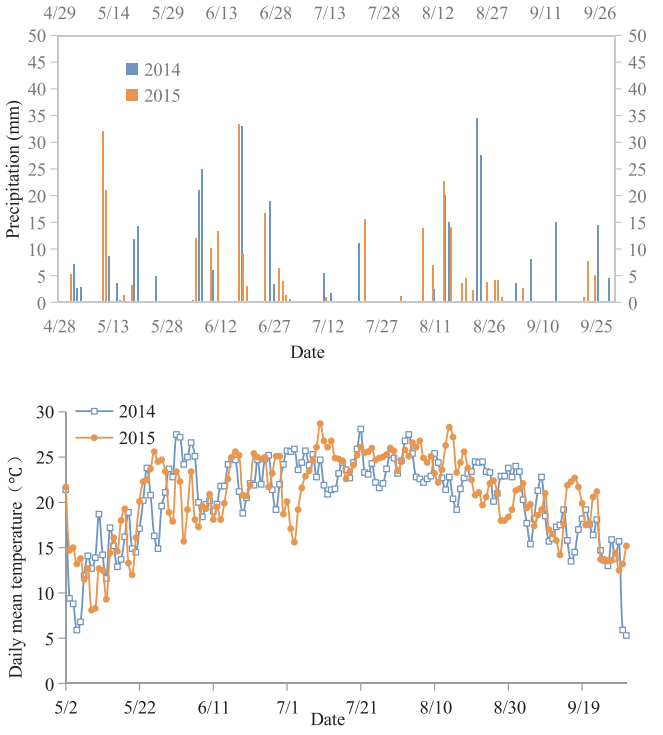

Fig. 1. Weather conditions at the experimental site in 2014 and 2015. Upper, rainfall. Below, daily mean temperature.

2. Materials and methods

2.1. Location and weather

Field experiments were conducted in 2014 and 2015 at two sites, Fu-jia-jie and San-ke-shu, Li-shu country (43°21′N, 124°05′E, 171 m above sea level), Jilin Province, China. The climate is sub-humid temperate with continental monsoons and an annual mean temperature of 11.6 °C. This area is typical of rain-fed spring maize production in Northeast China. The total rainfall during the 2014 and 2015 growth stages (May 1st to October 1st) were 342 and 290 mm, respectively (Fig. 1). Drought occurred in both years, but the time and degree of the droughts were different. In 2014, the rainfall was 156 mm from sowing to 8 expanding leaves (V8), 22 mm from V8 to V12, 21 mm from V12 to grain filling stage (R3), and 143 mm from R3 to maturity (R6). In 2015, rainfall was 132, 39, 42 and 77 mm for the same periods. The rainfall from V8 to V12 and V12 to grain filling stage (R3) in 2014 was lower than that observed in 2015, while the rainfall from R3 to R6 was 66 mm higher in 2014 than in 2015.

The soil type is loamy sand in Fu-jia-jie, whereas in San-ke-shu, the soil type is clay loam – according to the United States Department of Agriculture Soil Taxonomy system (Soil Survey Staff, 1998). The bulk density and field capacity of these soil types are presented in Table 1S.

2.2. Field design and experimental treatments

The field experiment was conducted using a randomized complete block design with five fertigation treatments in two soil type (sandy and clay soil); each treatment was replicated four times. The plots were 25 m × 6 m in size, with ten rows in each plot. The treatments applied were as follows: (1) conventional (CK) - all fertilizers were applied as basal fertilizer and the field was not irrigated; (2) drip irrigation (DI) - all fertilizers were applied as basal fertilizer and the field was irrigated by drip irrigation; (3) surface drip fertigation (SDF) – fertilizers were applied as basal application plus top dressing during the maize growth period using a drip irrigation system; (4) subsurface drip fertigation

(SSDF) – the capillary pipes were laid 30 cm below the soil surface and the fertilizer application method was the same as in the SDF treatment; (5) surface drip fertigation and plastic mulch (SDFP) – in addition to fertigation, a plastic film was used to cover the soil surface before sowing. A hole was made in the plastic to let the seedling grow out, and the fertilizer application method was the same as in the SDF treatment.

Fertilizers were applied according to a target yield level of 12 ton ha^{-1}. The fertilizer input amounts for the 2014 treatments were: 240 kg N ha^{-1}, 122 kg phosphorus pentoxide (P_2O_5) ha^{-1} and 119 kg potassium oxide (K_2O) ha^{-1}. In 2015, the amounts were: 240 kg N ha^{-1}, 100 kg P_2O_5 ha^{-1} and 113 kg K_2O ha^{-1}. For the CK and DI treatments, all the N, P, K was supplied at sowing as basal application using a compound fertilizer (N-P_2O_5-K_2O:28-12-12), potassium chloride, and super calcium phosphate. For drip fertigation treatments, a compound fertilizer of 15-15-15 was applied as basal fertilizer, which included 30%, 82% and 76% of the total N, P and K inputs in 2014, and 30%, 72% and 64% in 2015. The remaining N, P, K was supplied by a fertigation system at eight growth stages using urea (46% N) and a soluble compound fertilizer (N-P_2O_5-K_2O:30-6-12) from GAP agricultural technology company. The fertilizer amount for each application is recorded in Table 1.

2.3. Irrigation system and irrigation scheduling

The maize was planted in a twin-row pattern (Fig. 1S), that is, the distance between the two rows is 40 and 80 cm alternately. The main pipes were laid vertical to the row direction at the front of the plots. The capillary pipes were only placed between the narrow rows. For subsurface drip irrigation, the drip-line was installed at a depth of approximately 30 cm below the soil surface. The emitters were spaced along the drip lateral at 30 cm apart and the emitter discharge rate was 1.05 L h^{-1}. A pump was provided for each plot.

In 2014, the maize hybrid – cv. Liangyu 11 – was sown on 6th May and harvested on 30th September, whilst in 2015, the maize was sown on 2nd May and harvested 1st October. Planting density was 70,000 plants/ha. Weeds, diseases and pests were well controlled using herbicides and pesticides. Irrigation amounts and timings were scheduled to supplement rainfall and meet crop water requirements (e.g. crop evapotranspiration). Detailed irrigation records are shown in Table 1. The basic soil physicochemical properties are listed in Table 3S.

Table 1
Schedule of water and nutrient management for drip irrigation and fertigation.

Date	Irrigation amount (mm ha^{-1})		Fertilizer amount (kg ha^{-1})		
2014	Clay	Sandy	N	P_2O_5	K_2O
5/2	0	0	72	100	90
5/10	0	0	0	0	0
6/18	10	10	18	7	7
6/30	10	10	18	0	0
7/9	10	10	30	6	12
2014/7/18(VT,Silking stage)	10	10	30	0	0
7/27	10	20	24	10	10
8/2	10	38	24	0	0
8/14	10	10	12	0	0
8/24	10	10	12	0	0
Total	80	118	240	122	119

Date	Irrigation amount (mm ha^{-1})		Fertilizer amount (kg ha^{-1})		
2015	Clay	Sandy	N	P_2O_5	K_2O
5/4	0	0	72	72	72
5/10	40	0	0	0	0
6/16	10	10	18	7	7
6/26	8	5	18	0	0
7/10	8	8	30	6	12
7/16	6	15	30	6	12
2015/7/25 (VT, Silking stage)	10	10	24	10	10
8/4	10	10	24	0	0
8/14	10	10	12	0	0
8/26	8	10	12	0	0
Total	110	78	240	100	113

2.4. Maize yield, yield components and nutrient uptake

On physiological maturity of the crop, the yield and its components were determined by harvesting an area of 20 m^2. Grain was oven-dried to determine grain moisture at harvest. Grain yield was standardized to 14% moisture. Ten plants from each plot were harvested randomly to determine the grain number per cob and 100-grain weight. For plant dry matter and nutrient analyses, plants were cut at the soil surface and separated into leaves, stems (comprising the leaf sheath, tassels and ear shoots) and grains at V8, V12, VT, R3 and R6 stages. Three plants were then randomly taken from each plot. The samples were dried in an oven at a temperature of 70 °C and were then weighed. Dry matter accumulation of the plant was calculated. Then the samples were ground into powder for measuring the nutrient content. N concentration was determined by the semi-micro Kjeldahl method. P was measured spectrophotometrically using the molybdo-vanadophosphoric acid method. K was determined by flame photometry (Bao, 2000). The leaf area index (LAI) refers to the total leaf area per sampling area. The leaf area was calculated as leaf length × maximum width × 0.75 at V8, VT and R3 stages (Lu et al., 2014).

2.5. Soil nitrate as nitrogen concentration and residue

Two soil samples from each plot were collected randomly at 0–80 cm beneath the soil surface using an auger at V8, V12, VT, R3 grown stages. At sowing and final harvest, two soil samples were collected randomly from each plot at 0–200 cm below the soil surface using an auger. Each sample was divided into four layers at 20 cm intervals at V8, V12, VT, R3 stages (0–80 cm), and was divided into ten layers at 20 cm intervals at sowing and final harvest stages (0–200 cm). Soil samples were extracted with 0.01 mol L^{-1} calcium chloride, and analyzed for nitrate as nitrogen (NO_3-N) using a continuous flow analyzer (TRAACS 2000, Bran and Luebbe, Norderstedt, Germany). The NO_3-N amount per unit area was calculated as:

$$A = D \times \gamma \times C \times 0.1$$

Where A is soil NO_3-N amount per ha (kg ha^{-1}), D is the soil thickness (cm), γ is soil bulk density (g cm^{-3}), C is soil NO_3-N content (mg kg^{-1}) and 0.1 is the conversion factor (Duan and Su, 2002).

2.6. Soil moisture and crop evapotranspiration

At sowing and final harvest, two soil samples were collected randomly from each plot at 0–200 cm below the soil surface using an auger. Soil water content was determined by the gravimetric method (oven dry basis). Since the plant had eight expanded leaves. From stage V8, soil moisture content was also monitored once every 2–3 days using time domain reflectometry (TDR) (TRIME-PICO-IPH TDR, Germany, IMKO; Topp et al., 1980). The access tube is placed in the center of the narrow and the wide row in each plot. Measurement was done d every 20 cm from the surface of the soil to a depth of 80 cm. Data from the TDR (volumetric water content: cm^3 cm^{-3}) was recalculated into water content per unit of soil weight using the formula: water content (%, g g^{-1}) = (ρ_w / ρ_s) W_v, where ρ_s is the bulk density of the soil, ρ_w is the density of water (this usually may be taken as unity in g cm^{-3}units, ρ_w = 1.0 g cm^{-3}), and W_v is the volumetric water content (Klute, 1988). Total water consumption (Actual crop evapotranspiration) under the different irrigation treatments was calculated using the soil water balance equation (El-Hendawy and Schmidhalter, 2010; Zhang et al.,

2017).

$$ET = P + I + Cr - R - D \pm \Delta S$$

Where ET represents seasonal crop evapotranspiration (mm), P is precipitation (mm), I is the amount of irrigation water, Cr is the capillary rise (mm), R is the amount of run off (mm), D is the amount of drainage water below the 200-cm soil layer (mm), and ΔS is the difference between soil water content values in 0–200 cm soil depth at planting and at the end of harvesting (mm). Because the soil surface was flat and the groundwater table was 10 m below the soil surface, the values of R and Cr were considered negligible. When the sum of the soil water storage (SW) in the 0- to 200-cm soil profile and the precipitation was greater than the field capacity (FC), it was assumed that the excess water percolated into the deeper zones. Because the rainfall was low in 2014 and 2015, D was also neglected in this study.

2.7. Fertilizer and water productivity

Partial Fertilizer productivity (PFP) is calculated as: PFP (kg kg^{-1}) = grain yield / nutrient input, in which nutrient input including N, P_2O_5 and K_2O (Zhang et al., 2008).Water productivity (WP) is calculated as: WP (kg $mm^{-1} ha^{-1}$) = Grain yield / evapotranspiration (Arbat et al., 2010).

2.8. Statistical analyses

After verifying the homogeneity of error variances, the data (yield, yield components, nutrient accumulation, PFP, water productivity, LAI, dry matter accumulation, nutrient uptake rate and soil NO_3-N content) across soil type, year of production and nutrient management strategy were pooled for a variance analysis with a three-factor variance analysis program using the ANOVA procedure (SAS/STAT, SAS institute, 1988). The soil type, year of production and nutrient management were considered as fixed effects. The data for N residue, total N uptake and apparent N loss across nutrient management strategies and soil type were subjected to a variance analysis with a two-factor variance analysis program in SAS. The means were compared using Fisher's protected LSD at a probability level of 0.05.

3. Results

3.1. Soil moisture content

Previously it was found that the permanent wilting points of the sandy and clay soil in the experimental region is 6.4% and 10.1%, respectively, which is equivalent to 35% and 40% of the field capacity, respectively (Li et al., 2017). In 2014, severe droughts occurred mainly 10 days before and 20 days after VT (20 July). Under the CK treatment on sandy soil, the soil moisture content at the 0–20 cm and 20–40 cm soil layers was lower than 8% from 1 July (V12) to 15 August (R3), and the soil water content remained 4.5–6% from mid-July to mid-August (Fig. 2). In addition, the soil water content at the 40–60 cm and 60–80 cm layers decreased gradually. For the DI, SDF, SSDF and SDFP treatments, under which water was supplemented via drip irrigation, the soil moisture content at the 0–80 cm soil layer remained at 7–12% from mid-July (VT) to late September (R6). However, for the SSDF treatment, soil moisture content at the0–20 cm soil layer was lower than under DI, SDF and SDFP during the VT and late filling stages. In 2015, rainfall was very low during the maize growth season except for mid-August. The soil moisture content was lower under the CK treatment than the other treatments throughout the maize growth period.

The clay soil had a high field water capacity, ranging from 24 to 28% in the 0–80 cm soil layer (Table 1S). Under the CK treatment in 2014, the soil moisture content remained above 12% at 0–20 cm soil depth, above 14% at 20–40 cm soil depth and above 16% at 40–80 cm soil depth. Under the same treatment in 2015, the soil moisture content was lower at 0–20 cm deep than that observed in 2014 – at 9–18% during the whole growth period. The soil moisture content under the DI, SDF, SSDF, and SDFP treatments was higher than for the CK treatment at the VT and late filling stage, especially at 0–40 cm depth. Soil moisture content was lowest under the SSDF treatment at 0–20 cm soil depth compared to the other treatments.

3.2. Soil NO_3-N content

Soil NO_3-N was affected by soil type, year of production and management strategy during the various growth stages. The interactive effect between soil, year and management strategy was mostly not significant (Table 2S). So the effect of different management methods was analyzed by the average value across two years (Fig. 3). In sandy soil, soil NO_3-N content under CK and DI was higher than under SDF, SSDF and SDFP in 0–80 cm soil depth at V8 stage and in 0–20 cm soil depth at VT stage. But soil NO_3-N content under SDF, SSDF and SDFP was slightly or significantly higher than under CK and DI in 0–40 cm soil depth from filling (R3) to maturity (R6) stage. In clay soil, soil NO_3-N content under CK and DI was higher than under SDF, SSDF and SDFP in 0–60 cm soil depth at V8 stage, and there was no significant difference between treatments in most soil depths at VT, R3 and R6 stage except that SSDF was higher than CK and DI in 20–40 cm soil depth at R3 and R6 stage.

3.3. Nitrogen (N), phosphorus (P), and potassium (K) uptake rate and accumulation in the plant

Total aboveground accumulation of N, P and K was affected by soil type, year of production, management strategy and soil × management (except for nitrogen), but not by the interaction of year × management or year × soil × management (Table 2S). So, the two years' data were averaged to analyze the dynamic nutrient uptake rate through the growth season and nutrient accumulation in pre- and post-silking stages in the two soils (Figs. 4–6, and Table 2).

In the sandy soil, compared to SDF, SSDF and SDFP, N uptake rate under CK and DI was higher from V8 to V12 stage but lower from VT to R3 stage (Fig. 4). Therefore, N accumulation in SDF, SSDF and SDFP was lower at the pre-silking stage and higher at the post-silking stage (Table 2). The N uptake rate of DI was higher than that of CK from VT to R3 stage (Fig. 4), resulting greater post-silking N accumulation under DI compared to CK. There was no difference in total N accumulation between the DI, SDF, SSDF, SDFP treatments, all were higher than that of CK. In clay soil, the N uptake rate was similar under all treatments at the pre-silking stage, but was lower under CK and DI compared to SDF, SSDF and SDFP from VT to R3 stage. As a result, post-silking N accumulation was greater under SDF, SSDF and SDFP than in DI and CK. DI also increased post-silking N accumulation compared to CK. For both soil types, total N accumulation was similar among the DI, SDF, SSDF and SDFP treatments, all higher than under CK.

In both soil types, there was no significant difference in phosphorus uptake rate among the treatments except for VT to R3 stage. Under the CK treatment, phosphorus uptake rate from VT to R3 stage was significantly lower than under the DI, SDF, SSDF, and SDFP treatments (Fig. 5). As a result, the total phosphorus accumulation levels of the DI, SDF, SSDF, and SDFP treatments were all higher than that of CK (Table 2). In sandy soil, the phosphorus uptake rate of SSDF was slightly lower than SDF and SDFP from V12 to R6 stage, and the total phosphorus accumulation at harvest was significantly lower than SDF and SDFP. There was no significant difference in phosphorus uptake rate at whole growth period and phosphorus accumulation at harvest between the DI, SDF, SSDF, and SDFP treatments in clay soil.

Potassium was mainly taken up before VT and the net potassium uptake rate was negative at late R3 stage, suggesting potassium loss from the plants at this late stage. Generally, potassium loss from the

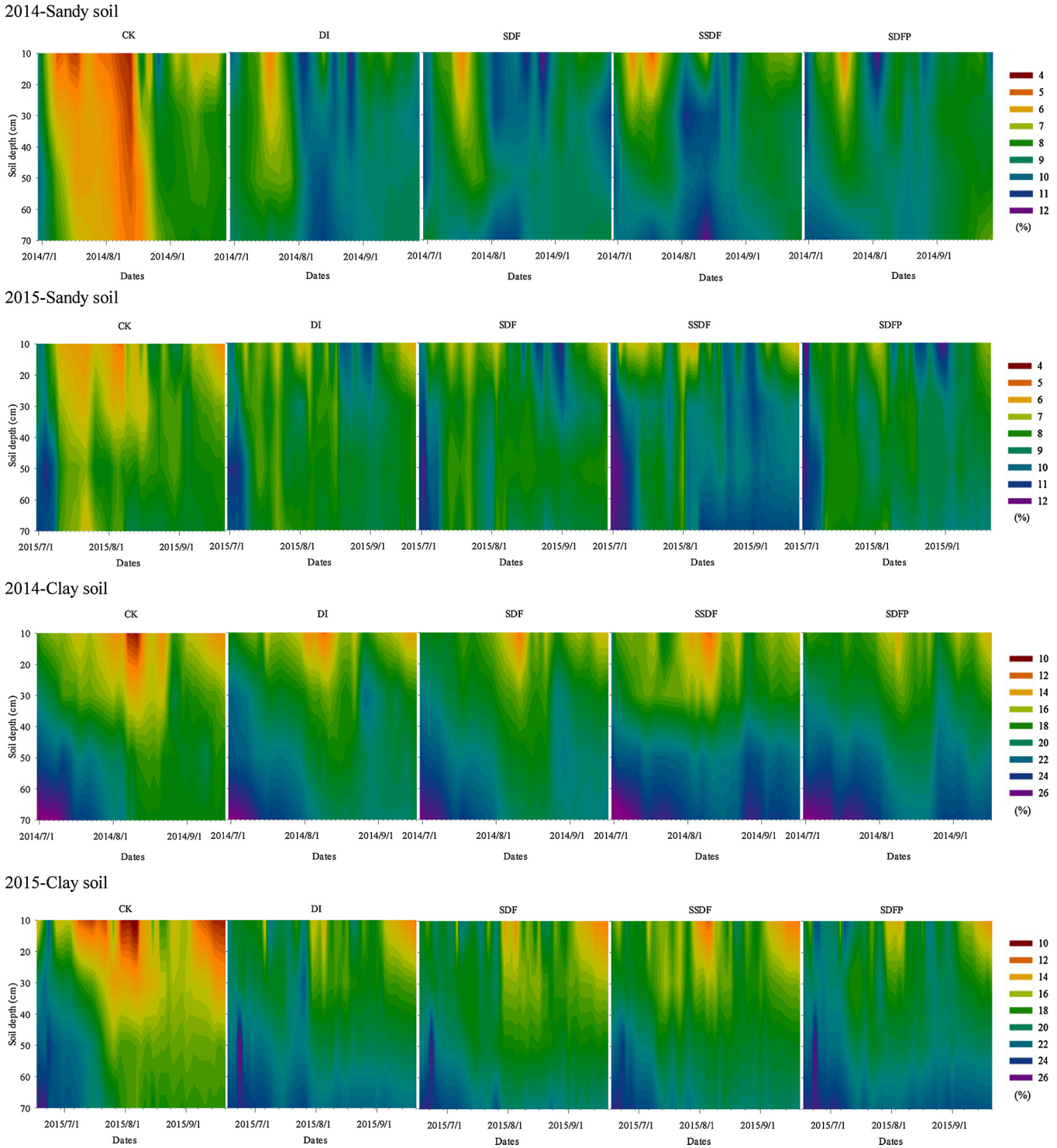

Fig. 2. Soil moisture content at different depths (0–20, 20–40, 40–60 and 60–80 cm) in the sandy and clay soil, 2014–2015. Values are mean of eight measurements (n = 8), two in each plot. CK: conventional; DI: drip irrigation; SDF: surface drip fertigation; SSDF: subsurface drip fertigation; SDFP: surface drip fertigation and plastic mulch.

plants occurred earlier under the CK treatment than in the other treatments. Potassium was lost from the plants by leaching and/or biomass loss (Fig. 6). In both soil types, DI and SDF increased potassium uptake rate from VT to R3 stage and the total potassium accumulation at harvest compared to CK, but no significant difference between SDF and DI. In sandy soil, SSDF did not increase the total potassium accumulation compared to CK, and significantly reduced the total potassium accumulation compared to SDF. In clay soil, SSDF significantly increased the total potassium accumulation compared to CK, but significantly reduced the total potassium accumulation compared to SDFP (Table 2).

3.4. Leaf area index (LAI) and dry matter accumulation

There was no significant difference in LAI between two years in clay soil, but the LAI in 2014 was significantly lower than that in 2015 in

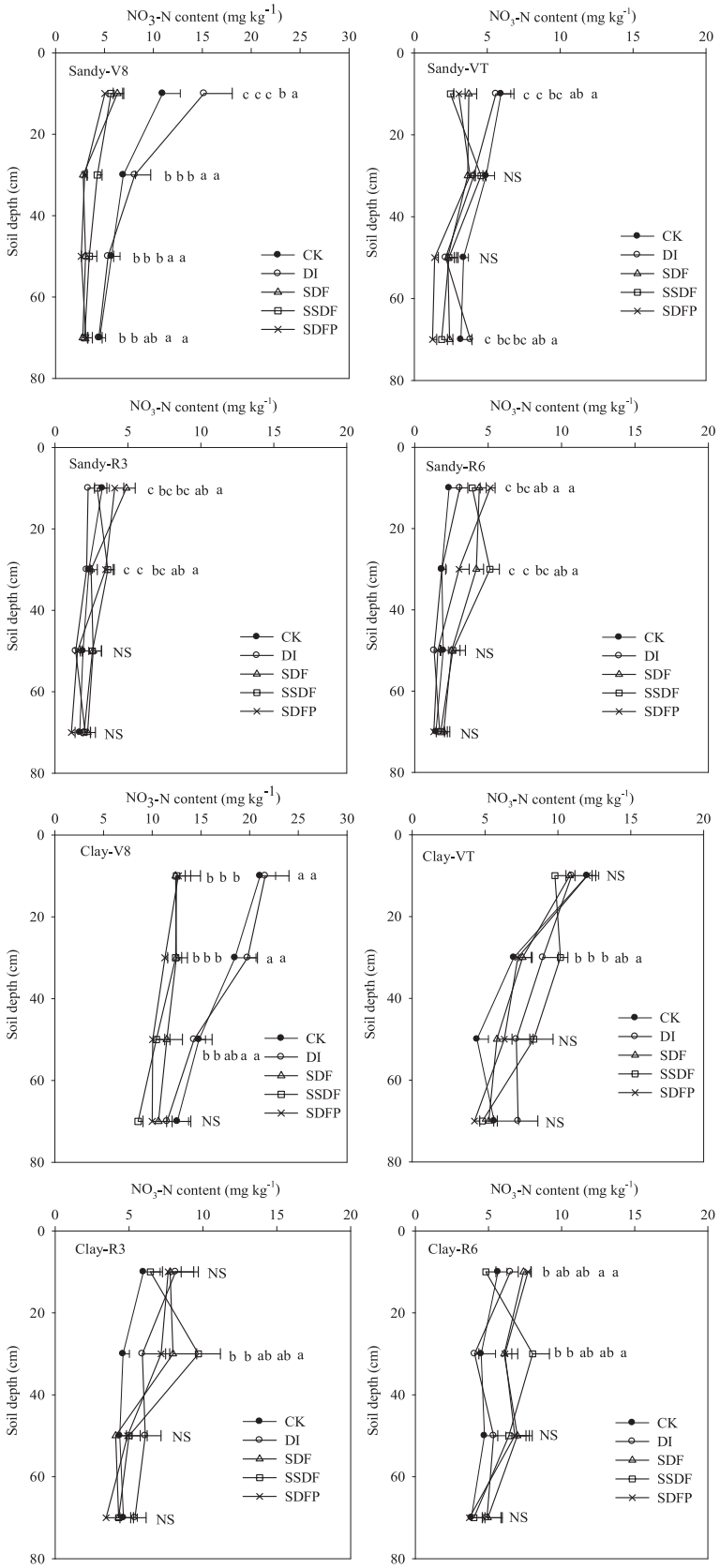

Fig. 3. Soil NO_3-N content on average of 2014 and 2015 at different depths (0–20, 20–40, 40–60 and 60–80 cm) in the sandy and clay soil. V8, the plant had 8 expanded leave; VT, Silking stage of Maize; R3, grain filling stage of Maize; R6,Maturity Stage of Maize. Values are mean ± SE (n = 8) of two years. At the same stage, means with different letters are significantly different at $P < 0.05$ according to LSD. CK: conventional; DI: drip irrigation; SDF: surface drip fertigation; SSDF: subsurface drip fertigation; SDFP: surface drip fertigation and plastic mulch.

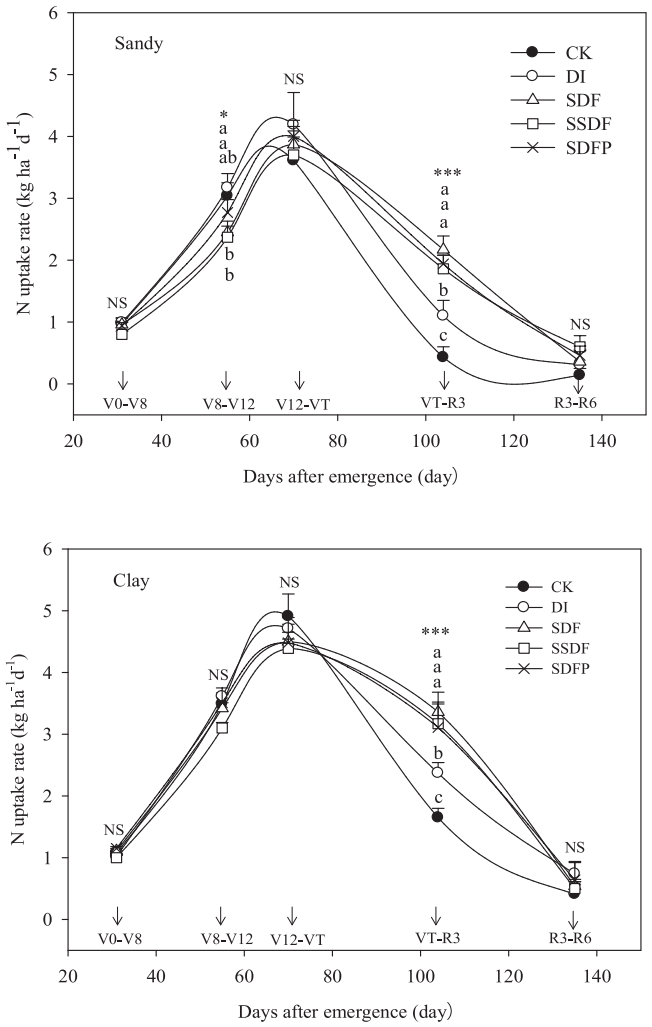

Fig. 4. Dynamic nitrogen uptake rate in the sandy and clay soil, 2014 and 2015. CK: conventional; DI: drip irrigation; SDF: surface drip fertigation; SSDF: subsurface drip fertigation; SDFP: surface drip fertigation and plastic mulch.

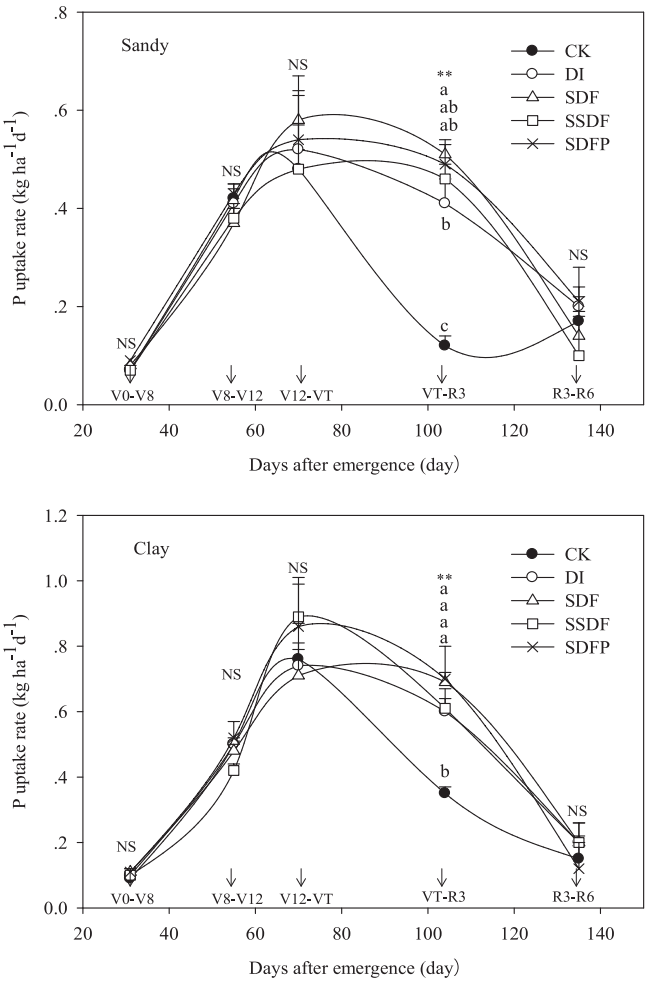

Fig. 5. Dynamic phosphorus uptake rate in the sandy and clay soil, 2014 and 2015. CK: conventional; DI: drip irrigation; SDF: surface drip fertigation; SSDF: subsurface drip fertigation; SDFP: surface drip fertigation and plastic mulch.

sandy soil (Table 5S). LAI was no affected by the interaction of management × year, and soil × year × management (Table 2S). Therefore the data of LAI in 2014 and 2015 were averaged to evaluate the effect of managements in two soils (Fig. 7). In sandy soil, SDFP increased LAI at the V8 stage. DI and all the fertigation treatments increased LAI at R3, but had similar LAI as CK at VT (Fig. 7). LAI under SSDF was lower than that of SDF at R3. In clay soil, LAI under DI and CK was the same throughout the maize growth season – lower than that of all the drip fertigation treatments at R3 but not at the vegetative stage.

In sandy soil, compared to the other treatments, dry matter accumulation under CK was lower during the post-silking stage, but not during the pre-silking stage (Fig. 8). Post-silking dry matter accumulation in SDF and SDFP was greater than that in SSDF and DI. Similarly, in clay soil, no difference in dry matter accumulation was observed at the pre-silking stage among all treatments either. During the post-silking stage, dry matter accumulation under CK was lower than under all other treatments. In 2014, no difference in final dry matter accumulation was found between DI, SDF, SSDF and SDFP. In 2015, the dry matter accumulation in DI was significantly lower than that of SDFP, but similar as that of SDF and SSDF. The difference between the three fertigation treatments was not significant.

3.5. Maize yield and yield components

Grain yield was affected by all treatments and all variable interactions except for year × management and soil × year × management. There was no significant difference in yields between two years in sandy soil, but the yield in 2014 was significantly higher than that in 2015 in clay soil (Table 5S). The two years data was averaged to analyze the management effect in the two soils (Table 3). In sandy soil, DI increased grain yields by 28%. SDF, SSDF and SDFP further increased grain yields compared to CK, by 41%, 36% and 41%, respectively (Table 3). Under DI, 100-grain weight and the number of grains per ear were increased by 10% and 12% compared to CK. No difference was found in the number of ears per hectare. Under SDF, 100-grain weight, the number of grains per ear and the number of ears per hectare were significantly increased by 21%, 11% and 5% compared to CK. The average maize yield under SDF and SDFP were significantly increased by 10% and 10% compared to DI mainly due to the higher 100-grain weight, but no significant difference between SSDF and DI. There were no significant differences in yield and yield components between SDF, SSDF and SDFP.

In clay soil, DI, SDF, SSDF and SDFP significantly increased grain yield with an average increase of 12%, 17%, 13% and 18% compared to CK (Table 3). The number of ears per hectare under DI was slightly greater, and the 100-grain weight and the number of grains per ear were significantly higher than CK by 6% and 4%. The number of ears per hectare and the 100-grain weight under SDF were higher than those

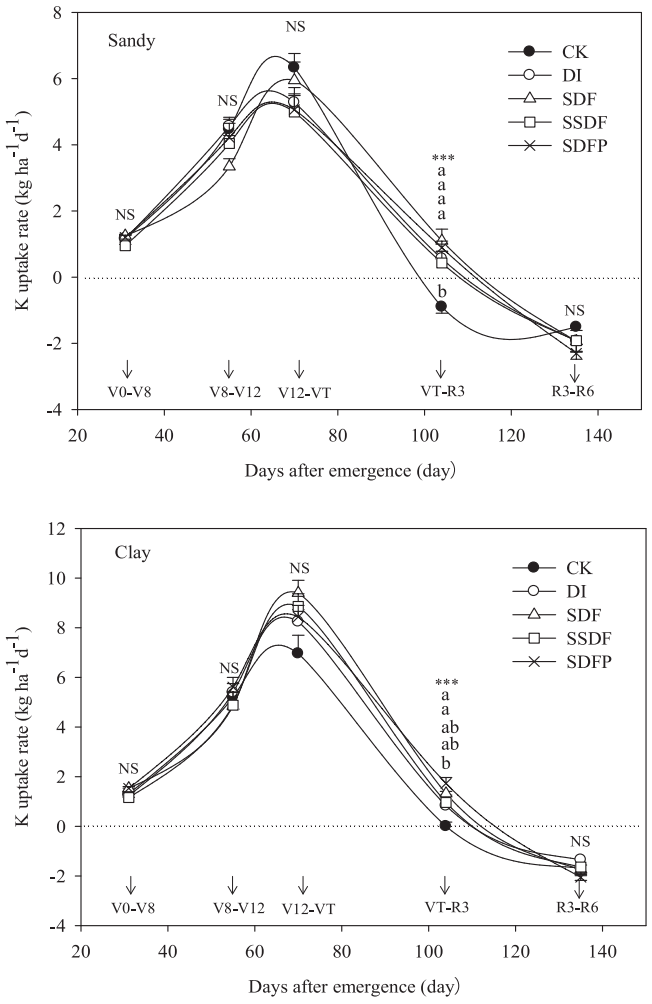

Fig. 6. Dynamic potassium uptake rate in the sandy and clay soil, 2014 and 2015. CK: conventional; DI: drip irrigation; SDF: surface drip fertigation; SSDF: subsurface drip fertigation; SDFP: surface drip fertigation and plastic mulch.

under CK by 6% and 10%, and the number of grains per ear was slightly greater. There were no significant differences in yield between DI, SDF and SSDF. Grain yield under SDFP was greater than under DI by 6%, however, no difference in yields was found between SDF, SSDF and SDFP.

3.6. PFP and water productivity

PFP and water productivity were affected by soil type, year, management strategy and soil × management, but not by the interaction of year × management and soil × year × management (Table 2S). In sandy soil, The PFP in 2015 was significantly higher than that in 2014, while there was no significant difference in PFP between the two years in clay soil (Table 5S). For different fertigation treatments, because the fertilizer amount for each treatment was the same, the difference in PFP between treatments was similar to that of yield (Table 4). The values of PFP in the two years were averaged to analyze the management effect in two soil types (Table 4). In sandy soil, DI increased PFP by 28% compared to CK, and SDF, SSDF and SDFP increased PFP by 41%, 36% and 41% respectively compared with CK. There was no significant difference in PFP between the three drip fertigation methods. In clay soil, DI, SDF, SSDF and SDFP significantly increased PFP by12%, 18%, 13% and 19% compared to CK, respectively. There was no significant difference in PFP between the three drip fertigation methods.

In sandy soil, there was no difference in water consumption between the DI, SDF, SSDF and SDFP treatments; all had higher values than that of CK. Water productivity under DI was the same as under CK. Water productivity under SDF, SSDF and SDFP was higher than under CK, by 17%, 8% and 14%, respectively. There was no significant difference in water productivity between the three drip fertigation methods. In clay soil, water consumption under DI and SDF was higher than under CK, but there was no difference in water consumption between SSDF, SDFP and CK. There was no difference in water productivity between DI and CK. However, water productivity under SDF, SSDF and SDFP was higher than under CK by 11%, 8% and 14% respectively. Furthermore, water productivity under SDFP was higher than SSDF. In both soil types, the water productivity in 2015 is significantly higher than in 2014 (Table 5S), mainly due to the decrease in rainfall in 2015 and the decrease in total water consumption.

3.7. Soil NO_3-N residue and apparent N loss

In both soils, compared to CK, DI reduced apparent N loss. Fertigation treatments reduced apparent N loss at greater extent than DI (Table 5). In general, DI and drip fertigation treatment did not affect soil NO_3-N residue in the soil at the end of the experiment.

3.8. Cost-benefit analysis of different management methods

In sandy soil, the net profit of DI, SDF, SSDF and SDFP was 13%, 28%, 31% and 10% higher than that of CK, respectively (Table 6), in spite of the high input of the drip irrigation system. SDFP management had lowest benefit because its highest costs which comes from the

Table 2
Effect of drip fertigation on the accumulation of N, P, and K in the plant on average of 2014 and 2015 on sandy soil and clay soil.

Soil	Treatments	Nutrient accumulation (g plant^{-1})								
		Total N at harvest	Pre-silking N accumulation	Post-silking N accumulation	Total P at harvest	Pre-silking Paccumulation	Post-silking Paccumulation	Total K at harvest	Pre-silking Kaccumulation	Post-silking Kaccumulation
Sandy	CK	2.51 b	2.30 a	0.21 c	0.45 c	0.23 ab	0.22 c	1.88 c	3.39 a	−1.51 a
	DI	2.97 a	2.27 a	0.69 b	0.61 a	0.25 a	0.36 ab	2.27 a	3.02 b	−0.74 b
	SDF	3.17 a	1.93 b	1.24 a	0.61 a	0.24 a	0.37 ab	2.19 ab	2.62 c	−0.48 c
	SSDF	3.02 a	1.80 b	1.21 a	0.55 b	0.21 b	0.34 b	1.84 c	2.76 bc	−0.92 b
	SDFP	3.11 a	1.81 b	1.27 a	0.64 a	0.25 a	0.39 a	2.05 bc	2.85 bc	−0.80 b
Clay	CK	3.6 c	2.51 a	1.14 c	0.61 b	0.32 b	0.29 c	2.83 c	3.52 b	−0.70 a
	DI	4.0 b	2.42 ab	1.64 b	0.75 a	0.33 b	0.42 a	3.52 ab	3.77 ab	−0.26 b
	SDF	4.2 ab	2.39 ab	1.82 a	0.75 a	0.32 b	0.43 a	3.46 ab	3.8 ab	−0.34 b
	SSDF	4.1 b	2.26 b	1.78 a	0.77 a	0.35 ab	0.42 ab	3.31 b	3.69 b	−0.38 b
	SDFP	4.3 a	2.42 ab	1.87 a	0.75 a	0.38 a	0.37 b	3.72 a	4.03 a	−0.35 b

Means with different letters are significantly different at $P < 0.05$ according to LSD. CK: conventional; DI: drip irrigation; SDF: surface drip fertigation; SSDF: subsurface drip fertigation; SDFP: surface drip fertigation and plastic mulch.

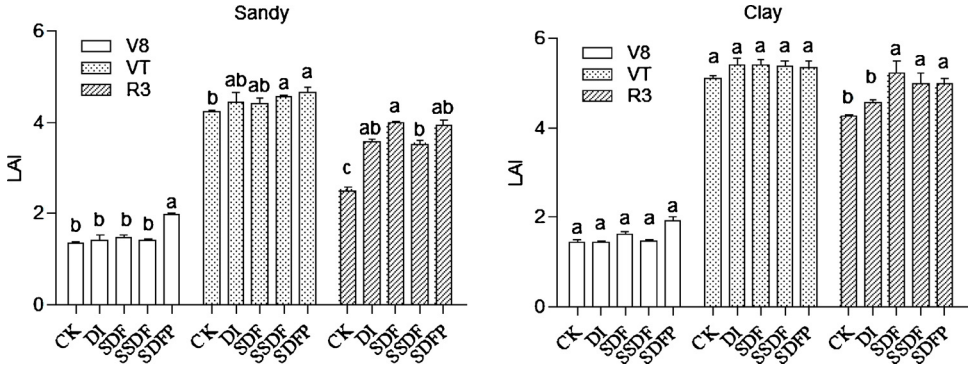

Fig. 7. Leaf area index on average of 2014 and 2015at different growth stage (V8, VT and R3) in the sandy and clay soil. At the same stage, means with different letters are significantly different at $P < 0.05$ according to LSD. CK: conventional; DI: drip irrigation; SDF: surface drip fertigation; SSDF: subsurface drip fertigation; SDFP: surface drip fertigation and plastic mulch.

additional inputs for buying the plastic film, machinery laying of the plastic film, as well as the cleaning of the residual plastic film each year. In clay soil, there is essentially no advantage in net profit for either DI or fertigation managements compared to the CK. For SDFP, even a 9% reduction in net benefit was observed.

4. Discussion

4.1. Comparison of drip irrigation and drip fertigation management

Water optimization via DI increased maize yield significantly. The

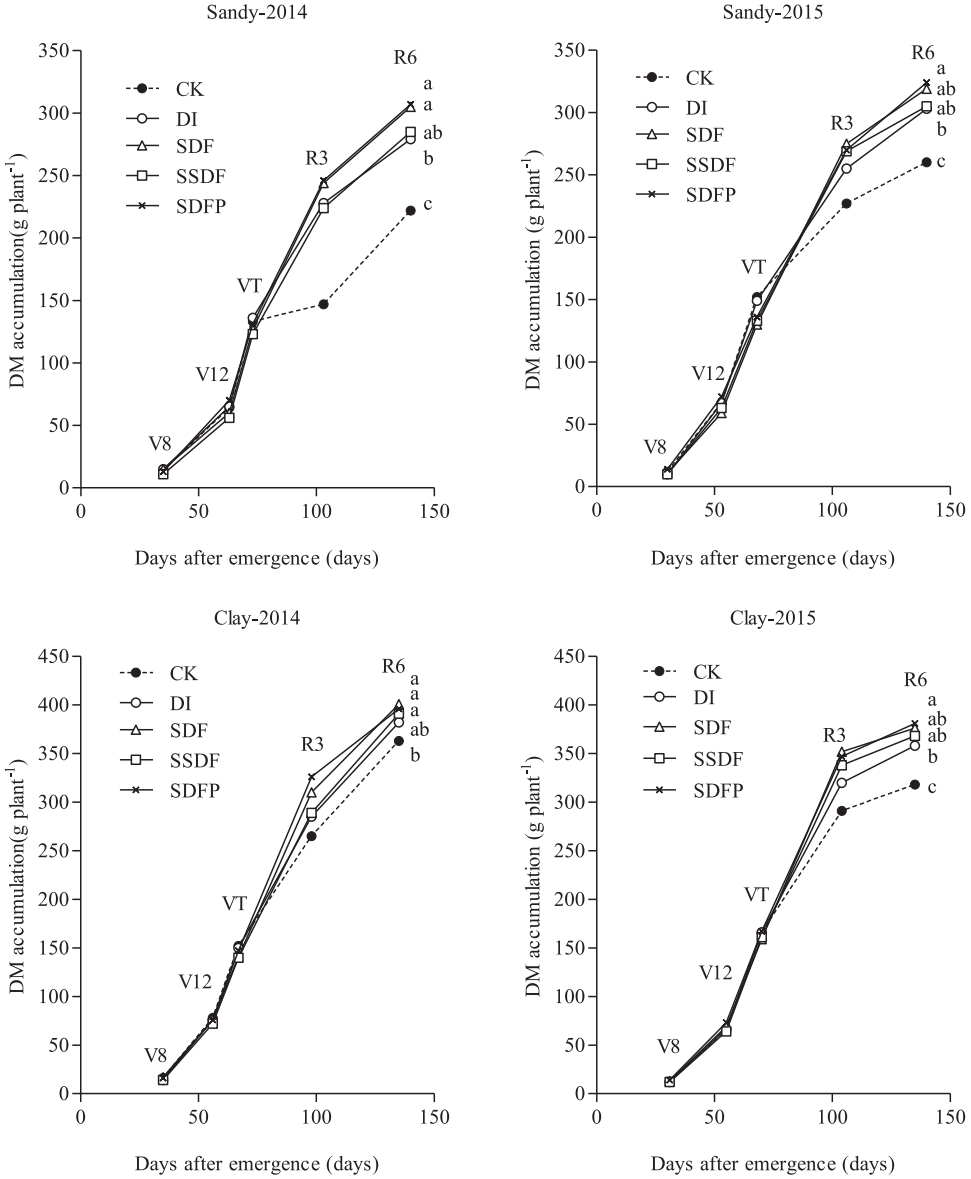

Fig. 8. Dry matter dynamic accumulation in the sandy and clay soil, 2014 and 2015. CK: conventional; DI: drip irrigation; SDF: surface drip fertigation; SSDF: subsurface drip fertigation; SDFP: surface drip fertigation and plastic mulch.

Table 3
Effect of drip fertigation on grain yield and yield components.

Soil	Treatments	Yield (kg ha^{-1})	Ear number (ha^{-1})	Grain number(ear^{-1})	100 Grain weight(g)
Sandy	CK	9394 c	64750 c	480 b	30 c
	DI	12041 b	67125 bc	537 a	33 b
	SDF	13223 a	68000 ab	531 a	37 a
	SSDF	12767 ab	68250 ab	524 a	36 a
	SDFP	13289 a	70500 a	534 a	35 a
Clay	CK	13281 c	66146 b	576 b	35 b
	DI	14845 b	67313 b	599 a	37 a
	SDF	15540 ab	70229 a	587 ab	38 a
	SSDF	14987 ab	68542 ab	586 ab	37 a
	SDFP	15688 a	68729 ab	601 a	38 a

Means with different letters are significantly different at $P < 0.05$ according to LSD. CK: conventional; DI: drip irrigation; SDF: surface drip fertigation; SSDF: subsurface drip fertigation; SDFP: surface drip fertigation and plastic mulch.

Table 4
Effect of drip fertigation on partial fertilizer productivity (PFP) and water productivity.

Soil	Treatments	PFP (kg yield kg^{-1} NPK)	Water consumption (mm)	Water productivity (kg ha^{-1} mm^{-1})
Sandy	CK	20 c	348 b	27 b
	DI	26 b	453 a	27 b
	SDF	28 a	422 a	32 a
	SSDF	27 ab	439 a	29 ab
	SDFP	28 a	433 a	31 a
Clay	CK	28 c	434 c	31 d
	DI	32 b	468 a	32 cd
	SDF	33 ab	463 ab	34 ab
	SSDF	32 ab	446 bc	33 bc
	SDFP	34 a	449 bc	35 a

Means with different letters are significantly different at $P < 0.05$ according to LSD. CK: conventional; DI: drip irrigation; SDF: surface drip fertigation; SSDF: subsurface drip fertigation; SDFP: surface drip fertigation and plastic mulch.

Table 5
Soil NO_3-N residue, total N uptake in two years and apparent nitrogen loss (the average value of two years in two soil type).

Soil	Treatments	NO_3-N content in 0-200 cm soil (kg ha^{-1})		Total N input in two years (kg ha^{-1})	Total N uptake in two years (kg ha^{-1})	Apparent N loss in two years (kg ha^{-1})
		Before sowing of 2014	At harvest of 2015			
Sandy	CK	76	65 b	480	325 c	166 a
	DI	76	66 b	480	398 b	92 b
	SDF	76	92 a	480	431 ab	33 c
	SSDF	76	85 ab	480	412 ab	59 bc
	SDFP	76	66 b	480	439 a	51 bc
Clay	CK	348	268 a	480	412 b	77 a
	DI	348	214 b	480	475 a	68 a
	SDF	348	259 ab	480	502 a	−23 c
	SSDF	348	238 ab	480	491 a	36 ab
	SDFP	348	234 ab	480	503 a	5 bc
Source of variation						
Soil			***		***	***
Treatments			NS		***	***
Soil*Treatments			NS		NS	NS

Apparent N losses were calculated as: Apparent N loss = soil mineral N (start) + N fertilizer - soil mineral N (end) – crop N uptake (Zhao et al., 2006). Means with different letters are significantly different at $P < 0.05$ according to LSD. CK: conventional; DI: drip irrigation; SDF: surface drip fertigation; SSDF: subsurface drip fertigation; SDFP: surface drip fertigation and plastic mulch.

Table 6
Input, average grain income and net economic profits of the different irrigation and fertilization methods.

Input item/Soils		CK	DI	SDF	SSDF	SDFP
Input		——————USD ha^{-1} $year^{-1}$)——————				
	Equipment	0	455	455	354	455
	Seed, chemical fertilizer and pesticide	664	664	755	755	755
	Machinery costs of field management	433	433	433	433	433
	Installation of drip irrigation equipment	0	91	91	46	91
	Pipe recycling every year	0	46	46	0	46
	Plastic film	0	0	0	0	91
	Laying plastic film	0	0	0	0	121
	Artificial handlig the seedlings	0	0	0	0	61
	Cleaning residual plantic film	0	0	0	0	91
	Total input	1096	1688	1780	1587	2144
Income	Sandy	2994	3838	4215	4070	4236
	Clay	4234	4732	4954	4777	5001
Net profit	Sandy	1898	2150	2435	2482	2092
	Clay	3137	3044	3174	3190	2857

Income is based on the average maize yield of 2014 and 2015. Maize price is USD 0.32 per kg according to the market. Drip irrigation equipment and their installation are based on a 10-year cycle. Only one installation is required for SSDF for a 10-year cycle. Income was calculated based on the average yield in 2014-2015. CK: conventional; DI: drip irrigation; SDF: surface drip fertigation; SSDF: subsurface drip fertigation; SDFP: surface drip fertigation and plastic mulch. The economic analysis was a very basic cost-benefit calculation.

yield increase in DI was mainly due to the increase of grain number per ear and 100-grain weight, which is most likely explained by the increasing soil humidity from V12 through to maturity (Fig. 2). Rainfall from 1 July (V12) to 13 August (R3) was only 21 mm in 2014 and 42 mm in 2015 (Fig. 1) and soil moisture content was very low in both years (Fig. 2). During this period, water supply is crucial for seed setting, pollination and early grain development. Water deficiency during this stage increases the interval between flowering and VT, and reduces the number of grains per ear (Bai et al., 2004, 2009). Nutrient availability and leaf longevity in the soil was closely related to water conditions. More grain number per ear and heavier grain weight in DI should be related to the increase in the uptake of N, P and K (Table 2) and also LAI at R3 stages as well. Due to increase in yield, DI increased fertilizer productivity of N, P, and K significantly (Table 4). DI did not increase the water productivity of maize, because water consumption increased with the increase of grain yield.

Compared to CK and DI, SDF provides a tool for synchronous improvement of water and nutrient management. In sandy soil, SDF increased maize yield to a greater extent than DI did (Table 3). One possible reason is that the post-silking uptake of N and P was higher in SDF compared to DI (Figs. 4 and 5). Similarly, SDF greatly improved soil water supply and also soil N supply at later growth, as indicated by the higher soil NO_3-N content under SDF compared to CK and DI in 0–40 cm soil depth from filling (R3) to maturity (R6) stage (Figs. 2 and 3). More post-silking nutrient uptake and reasonable water supply under SDF may have resulted in the longer leaf longevity and therefore greater post-silking dry matter accumulation. So, SDF had higher grain weight than DI, especially in sandy soil. Under high planting density like that in this experiment (70,000 plants ha^{-1}), the severe plant-to-plant competition for water, nutrient, and high frequently resulted in barren plants in which no fertile grains developed. Compared to DI, the ear number per ha at harvest generally increased in SDF, suggesting that the synchronous improvement of water and nutrient management is essential to reduce inter-plant competition. Most interestingly, the advantage of SDF over DI on plant growth and yield formation was not

dependent on more water consumption (Table 4). Therefore, water productivity in SDF was higher than that of DI. Finally, the apparent N loss was lower and soil NO_3-N residue was higher for SDF than DI, suggesting that the split-application of N may have reduced downward NO_3-N leaching. The lower NO_3-N residue in DI should not be due to the possible leaching after growth season because the soil is often frozen in the northeast from the harvest to the second year of sowing, and the rainfall is very low (e.g. 33 mm in 2014, 55 mm in 2015). Also the immobilization of nitrate-N should be very little because the negative charge of nitrate.

Water capacity and nutrient buffering ability are higher in clay soils compared to sandy soils (Nyvall, 2002; Warrick, 2018). There was less advantage of SDF over DI on grain yield, nutrient accumulation (except for post-silking N uptake), dry matter accumulation, PFP or water productivity. NO_3-N leaching into deeper soil is lower in clay soil compared to sandy soil types (Sogbedji et al., 2000; Beaudoin et al., 2005; van Es et al., 2006). Therefore, optimized water management via DI may be sufficient to maintain nutrient supply to meet maize growth demand, and the split application via SDF may not be so important. Nevertheless, in comparison to DI, SDF slightly increased soil NO_3-N content at R3 stages and R6 stages (Fig. 3), and then LAI was significantly increased at R3 stages (Fig. 7), and further SDF increased post-silking N uptake (Table 2) and greatly reduced N apparent loss (Table 5).

Both rainfall amount and its distribution affected corn growth. The rainfall amount in 2014 was higher in 2014 than in 2015. However, there was a severe short-term drought around silking stage in 2014. This short-term drought had a great negative effect on corn growth in sandy soil, but not in clay soil, as shown in LAI, grain number per ear, and grain yield (Table 5S). The possible reason should be that the clay soil had better water retention capacity so as to resist the short-term drought. In 2015 when there was less rainfall during the whole growth period, grain yield in clay soil was reduced, compared to that in 2014 (Table 5S).

4.2. SSDF and SDFP in comparison to SDF

Surface drip irrigation installations can have a long economic life when properly designed and managed. Long system life allows for amortizing investment costs over many years (Lamm, 2005). Generally, the effect of surface and subsurface drip irrigation on maize yield was similar (Camp, 1998; Howell et al., 1997; Camp et al., 1989). In the review of Sinobas and Rodríguez (2012), the efficiency of subsurface drip irrigation is similar to drip irrigation but it uses less water. It is also found that subsurface drip fertigation moved the center of the root density to a deeper depth, improve P use efficiency and increased maize yield (Hernandez et al., 1991; Phene et al., 1991). However, Lamm (2014) reported that, under drought conditions, the dry surface layer makes the pre-plant surface-applied N positionally unavailable to the crop, which lead to a yield reduction by 5–10%. The present study suggested that SSDF had similar effect as SDF in increasing grain yield and PFP (Tables 3 and 4). In sandy soil, the total accumulation of P and K in SSDF was less than that of SDF. The reason might be that the soil moisture content of the 0–20 cm soil layer was relatively lower under SSDF compared to SDF in some growth stage (Fig. 2), and also reduced the LAI at R3 stages (Fig. 7). Soil nutrients and maize roots are mostly distributed in the top 20 cm of the soil. Therefore, lack of water in this layer could affect soil nutrient mineralization and availability (Lamm, 2014), especially for P and K whose movements occur mostly via diffusion (Bar-Yosef et al., 1989; Hernandez et al., 1991). Cote et al. (2003) suggest that SSDF is not suitable forcoarse textured soils. Further, Scholberg and Dukes (2005) reported that the drip-line depth of SSDF at 33 cm was too deep on sweet maize under sandy soil. Nevertheless, SSDF had similar grain yield compared to SDF, suggesting the less uptake of phosphorus and potassium in SSDF in the present study is not essential for maize growth.

Plastic mulch is widely used in crop cultivation in China. It has dual functions –increasing soil temperature and maintaining soil moisture (Ma et al., 2007). There are reports indicating that SDFP can increase LAI, dry matter accumulation, N uptake and maize grain yield (Liu et al., 2011; Wei and Chen, 2011; Liu et al., 2014) mainly in the regions where thermal resources are limiting for maize growth (Ma et al., 2007). In the present study, it was shown that there was no significant difference in the yield between the three types of drip fertilization methods in both sandy and clay soil (Table 3). In clay soil, SDFP tended to had higher grain yield (and PFP and WP) compared to SDF and SSDF, possibly because soil temperature at early spring is much lower in clay soil than sandy soil, and mulching with the transparent plastic film can increase soil temperature and improve early seedling growth in clay soil, as shown in Fig. 7. However this effect seems quitted limited in the experimental area, and the advantage of SDFP over SDF gradually disappeared at late growth stage, as shown in leaf area, dry matter accumulation and yield for formation.

4.3. Economic consideration

Drip irrigation system is costly. Although drip irrigation or drip fertigation increased maize yield and fertilizer and water productivity, their feasibility depends on whether the net income is increased or not. In the sandy soil, DI and all the fertigation methods increased maize yield greatly compared to the CK. As a result, they also increased the net income. Especially, SDF and SSDF management had the highest net income, and therefore, can be recommended in maize production in sandy soil. Although SDFP had the highest maize yield, its cost was much higher than the other management methods. As a result, the net income of SDFP was lower than SDF and SSDF. In addition, the residual plastic film can cause environmental problem. Therefore, SDFP should not be recommended. In clay soil, the high costs for drip irrigation system was hardly balanced by the yield increase by either DI or drip fertigation managements. The net income even reduced in DI and SDFP in comparison to the CK. Therefore, either DI or any drip fertigation system is not recommended in the clay soil.

5. Conclusion

In conclusion, compared with the rain-fed maize, water optimization by drip irrigation improved maize growth and nutrient uptake, especially during post-silking stage. As a result, grain yield and fertilizer productivity were increased without sacrifice in water productivity. Synchronous water and nutrient optimization via drip fertigation increased maize yield and PFP to a larger extent than drip irrigation does. In addition, drip fertigation increased water productivity as well. No significant difference in grain yield, fertilizer productivity and water productivity was found between SDF, SSDF and SDFP management. The yield increase by DI and all the drip fertigation managements was much higher in sandy soil than in clay soil. In sandy soil, SDF and SSDF resulted in the highest net income and therefore should be recommended to the farmers. In clay soil, however, the high costs for drip irrigation system was hardly balanced by the yield increase by either DI or drip fertigation managements. Therefore, DI and drip fertigation management is not recommended in clay soil.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2018.10.018.

References

Arbat, G.P., Lamm, F.R., Kheira, A.A.A., 2010. Subsurface drip irrigation emitter spacing effects on soil water redistribution, corn yield, and water productivity. Appl. Eng. Agric. 26, 391–399.

Bai, L., Sui, F., Sun, Z., Ge, T., Lu, Y., Zhou, G., 2004. Effects of soil water stress on morphological development and yield of maize. Acta Ecol. Sin. 24, 1556–1560.

Bai, X.L., Sun, S.X., Yang, G.H., Liu, M., Zhang, Z.P., Hua, Q.I., 2009. Effect of water stress on maize yield during different growing stages. J. Maize Sci. 17, 60–63.

Bao, S.D., 2000. Soil and Agricultural Chemistry Analysis, third ed. China Agricultural Press, pp. 264–271.

Bar-Yosef, B., 1999. Advances in fertigation. Adv. Agron. 65, 1–77.

Bar-Yosef, B., Sagiv, B., Markovitch, T., 1989. Sweet corn response to surface and subsurface trickle phosphorus fertigation. Agron. J. 81, 443–447.

Barrett, C.B., 2010. Measuring food insecurity. Science (New York, N.Y.) 327, 825–828.

Beaudoin, N., Saad, J.K., Van Laethem, C., Machet, J.M., Maucorps, J., Mary, B., 2005. Nitrate leaching in intensive agriculture in Northern France: effect of farming practices, soils and crop rotations. Agric. Ecosyst. Environ. 111, 292–310.

Camp, C.R., Sadler, E.J., Busscher, W.J., 1989. Subsurface and alternate-middle micro-irrigation for the southeastern coastal plain. Am. Soc. Agric. Eng. 32, 451–456.

Camp, C.R., 1998. Subsurface Drip Irrigation: A Review. Transactions of the ASAE.41. pp. 1353–1367.

Chen, Y., Xiao, C., Chen, X., Li, Q., Zhang, J., Chen, F., Yuan, L., Mi, G., 2014a. Characterization of the plant traits contributed to high grain yield and high grain nitrogen concentration in maize. Field Crop Res. 159, 1–9.

Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., et al., 2014b. Producing more grain with lower environmental costs. Nature 514, 486.

Cote, C.M., Bristow, K.L., Charlesworth, P.B., Cook, F.J., Thorburn, P.J., 2003. Analysis of soil wetting and solute transportin subsurface trickle irrigation. Irrig. Sci. 22, 143–156.

Devasirvatham, V., 2009. A Review of Subsurface Drip Irrigation in Vegetable Production. Subsurface Drip Irrigation. Irrigation Matters Series No. 03-09.

Dong, Q., Li, M., Liu, J., Wang, C., 2011. Spatio-temporal evolution characteristics of drought of spring maize in northeast China in recent 50 years. Int. J. Nat. Disasters Health Secur. 20, 52–59.

Duan, Z., Su, 2002. Optimizing N rate under high yield corn cultivation system. Rev. China Agric. Sci. Technol. 4, 40–43.

El-Hendawy, S.E., Schmidhalter, U., 2010. Optimal coupling combinations between irrigation frequency and rate for drip-irrigated maize grown on sandy soil. Agric. Water Manag. 97, 439–448.

Enciso-Medina, J., Multer, W.L., Lamm, F.R., 2011. Management, maintenance, and mater quality effects on the long-term performance of subsurface drip irrigation systems. Appl. Eng. Agric. 27, 969–978.

Fanish, S.A., Muthukrishnan, P., Santhi, P., 2011. Effect of drip fertigation on field crops – a review. Agric. Rev. 32, 14–25.

Gao, Q., Feng, G.Z., Wang, Z.G., 2010. Present situation of fertilizer application on spring maize in Northeast China. Chin. Agric. Sci. Bull. 8, 1524–1534.

Gardenas, A.I., Hopmans, J.W., Hanson, B.R., Simunek, J., 2005. Two-dimensional modelling of nitrate leaching for variousfertigation scenarios under micro-irrigation. Agric. Water Manage. 74, 219–242.

Geng, G., Wu, J., Wang, Q., Lei, T., He, B., Li, X., et al., 2016. Agricultural drought hazard analysis during 1980–2008: a global perspective. Int. J. Climatol. 36, 389–399.

Godfray, H.C., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., et al., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812.

Hebbar, S.S., Ramachandrappa, B.K., Nanjappa, H.V., Prabhakar, M., 2004. Studies on NPK drip fertigation in field grown tomato. Eur. J. Agron. 21, 117–127.

Hernandez, J.J.M., Bar-Yosef, B., Kafkafi, U., 1991. Effect of surface and subsurface drip fertigation on sweet corn rooting, uptake, dry matter production and yield. Irrig. Sci. 12, 153–159.

Hodgson, A.S., Constable, G.A., Rochester, I.J., 1990. A comparison of drip and furrow irrigated cotton on a cracking clay soil, 1: growth and nitrogen uptake. Irrig. Sci. 11, 137–142.

Howell, T.A., Schneider, A.D., Evett, S.R., 1997. Subsurface and surface micro-irrigation of corn-southern high plains. Trans. Asae 38, 745–759.

Klute, A., 1988. Methods of soil analysis. Part1. Physical and mineralogical methods. Methods Soil Anal. Part. Phys. Mineral. Methods 146, 413–423.

Lamm, F.R., 2014. Irrigation and Nitrogen Management for Subsurface Drip Irrigated corn-25 Years of K-State's Efforts. ASABE Paper No. 141914980.

Lamm, F.R., 2016. Cotton, tomato, corn, and onion production with subsurface drip irrigation: a review. Trans. ASABE 59, 263–278.

Lamm, F.R., Trooien, T.P., 2003. Subsurface drip irrigation for corn production: a review of 10years of research in Kansas. Irrig. Sci. 22, 195–200.

Lamm, F.R., 2005. Advantages and disadvantages of subsurface drip irrigation. MonografíasIniaAgrícola 1–13.

Lekakis, E.H., Georgiou, P.E., Pavlatou-Ve, A., Antonopoulos, V.Z., 2011. Effects of fixed partial root-zone drying irrigation and soil texture on water and solute dynamics in calcareous soils and corn yield. Agric. Water Manag. 101, 71–80.

Liu, Y., Li, Y., Li, J., 2014. Effects of nitrogen management on the growth and yield of mulched and drip-irrigated maize in Northeast black soil regions. J. Hydraul. Eng. 45, 529–536.

Liu, Z.D., Xiao, J.F., Liu, Z.G., Nan, J.Q., Yang, D.C., 2011. Effects of different irrigation treatment on morphological indexes, water consumption and yield of maize under mulch drip irrigation. J. Irrig. Drain. Eng. 30, 60–64.

Li, X., Xiang, D., Han, J., 2009. Research on the development of agricultural water resources utilization in China. Water Conservancy Sci. Technol. Econ. 15, 1076–1077.

Li, X.F., Ma, S.Q., Jiang, L.X., Ji, R.P., Liu, J., Li, X.H., et al., 2017. Applicability test of two common indexes for spring maize drought grade in northeast china. Meteorol. Monthly 43, 1421–1429.

Lu, X., Li, Z., Bu, Q., Cheng, D., Duan, W., Sun, Z., 2014. Effects of rainfall harvesting and mulching on corn yield and water use in the corn belt of Northeast China. Agron. J. 106, 2175–2184.

Ma, S., Qi, W., Guo, J., Shen, Z., 2007. Geographical change law of effects of corn plastic mulching on increasing temperature and production in Northeast China. Trans. Chin. Soc. Agric. Eng. 23, 66–71.

Ma, S., Wang, Q., Wang, C., Guo, J., Liu, L., Shen, Z., Qian, X., Zhang, H., 2004. Test on cooling and frost damage prevention of corn using plastic mulching in Northeast China. Int. J. Nat. Disasters Health Secur. 13, 133–137.

Motesharezadeh, B., Etesami, H., Bagheri-Novair, S., Amirmokri, H., 2017. Fertilizer consumption trend in developing countries vs. developed countries. Environ. Monit. Assess. 189, 2–9.

Nyvall, J., 2002. Soil Water Storage Capacity and Available Soil Moisture. Food and Fisheries of British Columbia. Ministry of Agriculture. Agdex550, pp. 1–4.

Pablo, R.G., O'Neill, M.K., Mccaslin, B.D., Remmenga, M.D., Keenan, J.G., Onken, B.M., 2007. Evaluation of corn grain yield and water use efficiency using subsurface drip irrigation. J. Sustain. Agric. 30, 153–172.

Pelling, M., Maskrey, A., Ruiz, P., Hall, L., Peduzzi, P., Dao, Q.H., Mouton, F., Herold, C., Kluser, S., 2004. Reducing Disaster Risk: A Challenge for Development. United Nations Development Programme, New York, NY.

Phene, C.J., Davis, K.R., Hutmacher, R.B., Bar-Yosef, B., Meek, D.W., Misaki, J., 1991. Effect of high frequency surface and subsurface drip irrigation on root distribution of sweet corn. Irrig. Sci. 12, 135–140.

Rajput, T.B.S., Patel, N., 2006. Water and nitrate movement in drip-irrigated onion under fertigation and irrigation treatments. Agric. Water Manage. 79, 293–311.

Sampathkumar, T., Pandian, B.J., 2011. Nutrient uptake rate and relationship with grain yields of hybrid maize under drip fertigation. Madras Agric. J. 98, 151–153.

Institute, S.A.S., 1998. SAS User's Guide: Statistics. SAS Institute, Cary, NC.

Scholberg, J.M., Dukes, M.D., 2005. Soil Moisture controlled subsurface drip irrigation on sandy soils. Appl. Eng. Agric. 21, 89–104.

Soil Survey Staff, 1998. Keys to Soil Taxonomy.United States Department of Agri-culture, Natural Resources Conservation Service, Washington, DC, USA, pp. 328.

Sogbedji, J.M., Es, H.M.V., Yang, C.L., Geohring, L.D., Magdoff, F.R., 2000. Nitrate leaching and nitrogen budget as affected by maize nitrogen rate and soil type. J. Environ. Qual. 29, 1813–1820.

Solaimalai, A., Baskar, M., Sadasakthi, A., Subburamu, K., 2005. Fertigation in high value crops-a review. Agric. Rev. 26, 1–13.

Sui, J., Wang, J., Gong, S., Xu, D., Zhang, Y., Qin, Q., 2018. Assessment of maize yield-increasing potential and optimum n level under mulched drip irrigation in the northeast of china. Field Crops Res. 215, 132–139.

Sun, S.K., Wang, Y.B., Liu, J., Wu, P.T., 2016. Quantification and evaluation of water footprint of major grain crops in china. J. Hydraul. Eng. 47, 1115–1124.

Sinobas, L.R., Rodríguez, M.G., 2012. A review of subsurface drip irrigation and its management. Water Quality, Soil and Managing Irrigation of Crops. Dr. TeangShui Lee. InTech, 978-953-51-0426-1 Available from http://www.intechopen.com/books/water-quality-soil-and-managing-irrigation-of-crops/a-review-of-subsurface-drip-irrigation-and-its-management.

Topp, G.C., Davis, J.L., Annan, A.P., 1980. Electromagnetic determination of soil water content: application of TDR to field measurements. Water Resour. Res. 16, 574–582.

Ünlü, M., Kanber, R., Koç, D.L., Tekin, S., Kapur, B., 2011. Effects of deficit irrigation on the yield and yield components of drip irrigated cotton in a mediterranean environment. Agric. Water Manage. 98, 597–605.

van Es, H.M., Sogbedji, J.M., Schindelbeck, R.R., 2006. Effect of manure application timing, crop, and soil type on nitrate leaching. J. Environ. Qual. 35, 670–679.

Wan, S., Jiao, Y., Kang, Y., Hu, W., Jiang, S., Tan, J., Liu, W., 2012. Drip irrigation of waxy corn (Zea mays L. var. ceratina Kulesh) for production in highly saline conditions. Agric. Water Manage. 104, 210–220.

Wang, M., Wang, L., Cui, Z., Chen, X., Xie, J., Hou, Y., 2017. Closing the yield gap and achieving high n use efficiency and low apparent n losses. Field Crops Res. 209, 39–46.

Warrick, A.W., 2007. Soil water concepts, F. R. Lamm, F.R., Ayars, J. E., Nakayama, F.S. (Eds.), Microirrigation for crop production: Design, Operation, and Management. Amsterdam, The Netherlands, pp. 27-53.

Wei, Y.H., Chen, L.J., 2011. Influences of different irrigation schedules on growing status of maize with drip irrigation under plastic film. J. Northeast Agric. Univ. 42, 55–60.

Yang, X., Lin, E., Ma, S., Ju, H., Guo, L., Xiong, W., Li, Y., Xu, Y., 2007. Adaptation of agriculture to warming in Northeast China. Clim. Change 84, 45–58.

Yang, X.C., Ming, B., Tao, H.B., Wang, P., 2015. Spatial distribution characteristics and impact on spring maize yield of drought in Northeast China. Chin. J. Eco-agriculture 23, 758–767.

Zhang, F., Wang, J., Zhang, W., Cui, Z., Ma, W., Chen, X., Jiang, R., 2008. Nutrient use efficiencies of major cereal crops in china and measures for improvement. Acta Pedol. Sin. 45, 915–924.

Zhang, G.H., Liu, C.W.,C.H, Xie, R.Z., Ming, B., Hou, P. et al., 2017.Optimizing water use efficiency and economic return of super high yield spring maize under drip irrigation and plastic mulching in arid areas of China. Field Crop Res. 144, 62–68.211, 137–146.

Zhao, R.F., Chen, X.P., Zhang, F.S., Zhang, H.L., Schroder, J., Römheld, V., 2006. Fertilization and nitrogen balance in a wheat?maize rotation system in North China. Agron. J. 98, 938–945.

Zhao, J.F., Yang, X.G., 2009. Influence of climate warming on serious low temperature and cold damage and cultivation pattern of spring maize in Northeast China. Acta Ecol. Sin. 29, 6546–6551.